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THE STRENGTH OF THIN REINFORCED TUBES UNDER EXTERNAL PRESSURE

By

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REPORT OF WORK COMPLETED AND PROGRESS

OF EXPERIMENTS

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THE STRENGTH OF THIN REINFORCED TUBES UNDER EXTERNAL PRESSURE

SUMMARY

One hundred models representing the strength hull of a submarine have been tested.

Within the range of frame spacing used, formula (92), of Reference (1), appeared to give reliable values of collapsing pressure. Formula (96) predicted the number of lobes accurately through a wide variation of frame spacing, but gave very unreliable values of collapsing pressure. A multiplying constant varying from 0.4 to 2 is necessary with formula (96) to make the theoretical and experimental values agree.

No scale effect was evident.

The strength of a frame is not materially increased by decreasing the length of unsupported arc from 360 degrees to 90 degrees. The strength of frames does not effect the collapsing pressure of the shell if the failure occurs by pure instability, providing they are strong enough to resist collapse.

The length of the model is unimportant as long as the frame spacing remains constant.

The strength of the shell cannot be appreciably increased by using longitudinal straps to break up the lobe formation.

GENERAL THEORY

K. v. Sanden and K. Gunther (Werft und Reederei, (1920) heft 8, p. 163 ff.) have developed a theory for the strength of thin cylindrical tubes, strengthened only by circumferential frames, and subjected to a uniform external pressure both radially and longitudinally. Since no reliable data is available for checking the accuracy of their assumptions, a testing program has been undertaken at the U.S. Experimental Model Basin. The following formulae were derived by Sanden and Gunther, in which

P = external collapsing pressure

r = inside radius of shell

t = thickness of shell

A = cross-sectional area of frames

b = width of frame flange attached to shell

l = length of unsupported shell <u>between</u> frames

σ = stress

$$\alpha = 1.285/\sqrt{r \cdot t}$$

$$\beta = \frac{2\,N\,t}{\alpha(A + b \cdot t)}$$

$$N = \frac{\cosh \alpha l - \cos \alpha l}{\sinh \alpha l + \sin \alpha l}$$

$$L = \frac{\sinh \alpha l - \sin \alpha l}{\sinh \alpha l + \sin \alpha l}$$

(Note: The formulae are numbered to correspond to those in the original article.)

For longitudinal stress

$$\sigma_{long} = \frac{rp}{t}\left[\tfrac{1}{2} + 1{:}815\left(.85 - \frac{b\,t}{A + bt}\right)\frac{\sinh \alpha l - \sin \alpha l}{(1 + \beta)(\sinh \alpha l + \sin \alpha l)}\right] \qquad [82]$$

and for tangential stress

$$\sigma_{tang} = \frac{rp}{t}\left[1-2(.85-\frac{bt}{A+bt})\frac{.455 \sinh\frac{\alpha l}{2}\cos\frac{\alpha l}{2} - 1.545\cosh\frac{\alpha l}{2}\sin\frac{\alpha l}{2}}{(1+\beta)(\sinh\alpha l+\sin\alpha l)}\right] \quad [82a]$$

Usually the greater stress is longitudinal. Collapse will take place when either the longitudinal or the tangential stress reaches the yield point of the material. It is possible, then, to solve for the external collapsing pressure from (82) and (82a)

Whence

$$P = \frac{\frac{t}{r}\sigma_{yield}}{\frac{1}{2} + 1.815(.85 - \frac{bt}{A+bt})} \quad \frac{L}{1+\beta} \qquad [92]$$

and

$$P = \frac{\frac{t}{r}\sigma_{yield}}{1-2(.85-\frac{bt}{A+bt})\frac{.455 \sinh\frac{\alpha l}{2}\cos\frac{\alpha l}{2} - 1.545\cosh\frac{\alpha l}{2}\sin\frac{\alpha l}{2}}{(1+\beta)(\sinh\alpha l+\sin\alpha l)}} \qquad [92a]$$

That formula is considered determinative which gives the lower value of P.

However, since the cylinders are subjected to external pressure, failure may occur through instability. This method of collapse was first investigated theoretically by Unwin(Proc.Inst. Civ.Engr. Vol. XLVI (1875) p 225) who developed a formula that fit Fairbairn's (Phil. Trans. Vol. 148(1858) p 389) results very closely. Later Southwell (Phil. Trans. Royal Soc. Vol. 213(1914) p 187) went into the matter of instability in great detail. v Mises (Z.d.V.D.I. (1914) p 750) developed a formula for collapse by instability of a tube of infinite length strengthened by frames, and in

1918 (see reference to formula in Werft und Reederei, 1920, heft 8, p 220) he offered the following formula for tubes stiffened with frames and subjected to both radial and end load:

$$P_k = \left\{ \frac{\frac{E}{n^2}\,\frac{t}{r}}{\left[1+\left(\frac{n}{\pi}\,\frac{l}{r}\right)^2\right]^2} + \frac{n^2}{12}\left[1+\left(\frac{\pi}{n}\,\frac{r}{l}\right)^2\right]^2 \frac{m^2 E}{m^2-1}\left(\frac{t}{r}\right)^3 \right\} \frac{1}{1+\frac{1}{2}\left(\frac{\pi}{n}\,\frac{r}{l}\right)^2} \quad [96]$$

where n is the number of lobes into which the shell collapses.

In formula (96) there will be a certain number of lobes for which P is a minimum and this P will be the collapsing pressure provided that at that pressure neither equation (82) nor (82a) gives a value of σ beyond the <u>proportional</u> limit. If the stress in either of these equations does exceed the proportional limit, however, formula (96) can still be used approximately since the value of E can be roughly determined in this region for known stresses. (See v. Karman, Untersuchhungen uber Knickfestigkeit, Mitteilungen uber Forschungsarbeiten, heft 81, 1910).

FABRICATION OF MODELS

The first thing that became evident from our experiments was the tremendous influence on collapsing pressure of local irregularities or local out-of-roundness of the shell. It is obvious that if tests are to give any indication of the strength of full-size submarines, the models must be made with the same percentage of accuracy as the submarine hull; in other words, they must be geometrically similar. This percentage is not definitely known, but it is estimated that the total variation in radius throughout the circumference does not exceed one-half the shell thickness and that no local irregularities within a circumferential distance equal to one frame space are greater than one-fifth this amount. This means, in the case of a model 16" in diameter and .05" shell thickness, that the maximum radius cannot exceed the minimum by more than .025" and that the variation in radius in about 2½", measured circumferentially, cannot be greater than .005". This requires extreme care in the construction of the models, as well as accurate methods of measurement to determine the influence of local out-of-roundness.

Tubing of the required dimensions was not obtainable; hence, it was necessary to fabricate the models by rolling up a flat sheet of steel. For building the models, a plunger 4" high and 1" thick was turned to exactly 16" outside diameter. Since the shell thickness averaged .05", a ring 2" high and 1" thick was turned to an inside diameter of 16.10". This ring was made adjustable to accomodate slight variations of shell thickness. Great care must be used in fabricating the shell. A piece of material of the same thickness as the shell is first used to set the rolls for the required diameter. The shell is purposely cut about a foot too long. Each end is then run through the rolls for a distance of about 18", and the excess 6" length sawed off. Since the rolls are accurately set and the ends are already bent to the proper radius, the sheet can be run through and will close at the ends at the proper diameter. The outside ring is now fit snugly over the shell and the plunger is placed inside. By pushing both ring and plunger along with a press and soldering the seam after the plunger a very accurate model is formed. (See photographs).

RECORDING DEFORMATIONS

A measuring device was constructed for determining the actual initial contour of the shell and its shape at successive pressures as load was applied. (See photographs). Measurements could be taken at 1 degree intervals at any height desired. It was thus possible to plot the circumference of the model on polar coordinate paper, greatly magnifying the irregularities. Longitudinal measurements could also be made. (See sample data sheet).

APPLICATION OF FORMULAS

It is seen from equation (92) and from the accompanying L and N curves, that for values of αl of 6 or greater the collapsing pressure is independent of αl and therefore of the frame spacing. In the models used, with $r = 8''$ and $t = .050''$ $\alpha = 1.285/\sqrt{rt} \approx 2.03$. This means that for values of l greater than 3", formula (92) gives constant collapsing pressures and, therefore, no longer holds.

Now it so happens that this value of $\alpha l = 6$ is very near the desirable working range of l in a large submarine, or about 36". It is, therefore, a very important region. In this range, collapse likely occurs by instability. Unfortunately, the values of P obtained by (96) do not check well with experiment. The Germans had discovered this experimentally, but had attributed the lack of agreement to the fact that the models tested were not perfectly round. In Hilfsbuch fur den Schiffbau, by Johow-Foerster, Berlin 1920, is the following statement:

"Equation (3) (which is v Mises formula for collapse without end load, Z.d.V.D.I. 1914 p.750, and is practically equivalent to (96) for large values of n) gives values that are too high for practical work, since the theoretical assumptions cannot be fulfilled, owing to the unavoidable departures from the circular form. According to experiments conducted by the Germania Shipyward and by the Royal Dockyard at Danzig one will be on the safe side when for plate thicknesses up to 5 mm., (or .197"), P_k as found by equation (3) is multiplied by the coefficient 0.4; for thicknesses of 5-7 mm, (or .197"-.276"), by 0.5; and for those above 7 mm., (or .276"), by 0.6". And again, "even though in actual practice the preliminary conditions of the theory cannot be fulfilled and quite marked deviations from the circular form occur, nevertheless it is found that the number of bulges obtained from equation (3) corresponds in reality very well with the theory and that it gives very good values also for the collapsing pressure when the above mentioned coefficients are used." All this assumes, of course, that the limit of proportionality has not been exceeded.

Our experiments show that this is good agreement between the observed length of the bulges and the computed length obtained by dividing the circumference by the value of n that makes the value of P_k in (96) a minimum. The shell thickness of our 16" models was 0.050" or 1.27 mm. For this thickness the constant multiplier 0.4 is indicated. However, these models are constructed with the same degree of accuracy as the full scale submarine whose shell thickness is 0.588" or 15 mm., and here the above rule gives 0.6 as the constant. It seems reasonable to assume that this constant is not a function of the thickness itself, but rather of the accuracy with which a shell of that thickness can be fabricated.

Be that as it may, the use of any constant multiplier less than unity assumes that the theoretical collapsing pressure is above the experimental. Table I (next page) is taken from data sheet No. 3, showing the actual and theoretical collapsing pressures. (Note: The notation employed in numbering the models is as follows: S X are open head models, in which the measuring device could be used and which are known to be more accurately constructed. All other models are closed at both ends and nothing is certain about their departures from circular form. The second term, 179D, 154D, etc., means that the frame spacing is 0.179 and 0.154 times the diameter respectively, which for D = 16" gives 2.864" and 2.473". The term 50T refers to the approximate thickness and means that the thickness is about 0.050". 51C, 99U, 111 1, etc., gives the depth and type of frame, C referring to circular frames, U to channels and 1 to the cut I beams, while the 51, 99, etc., mean that the depth of the frame is 5.1 and 9.9 times the wall thickness. The numbers 1,2,3, following, differentiate identical models.)

Model	Unsupported length	Lbs. per sq. in Exp't P	Theoretical P For. (96)	For. (92)	Ratio Exp't Calc. (96)	Exp't Calc. (92)
SIII 6A	38.7	22	32.3		.68	
" 6B	"	27	31.4		.86	
" 6C	"	28	30.1		.93	
" 2	16	61	78.1		.78	
" 546D50T1	8.75	65	72.1		.90	
" 375D50T1	6	107	128.8		.83	
SV 179D50T51C1	2.739	122	240	129.1	.51	.95
SIV " " 75C	2.676	114	292	94.4	.39	1.21
SV " " "	"	96	218	87.2	.44	1.10
SX " " "	"	150	316	129.9	.47	1.15
SX 154D50T50C1	2.348	180	379	167.0	.47	1.08
" " " " 2	"	170	370	164.4	.46	1.03
SV 149D50T51C	2.259	115	272	110.8	.42	1.04
SX " " C1	"	115	290	117.9	.40	.98
SX " " C2	"	162	386	158.9	.42	1.02
" " " C3	"	170	394	160.6	.43	1.06
SIV " " 75C	2.196	125	350	85.0	.36	1.47
SVIII " "	"	127	355	85.6	.36	1.48
SV " " "	"	110	256	82.9	.43	1 33
SX 154D50T99U1	2.185	170	343	172.4	.50	.99
SX " " U2	"	165	339	171.1	.49	.96
" " " U3	"	155	339	171.1	.46	.91

We see that for models with a fairly long unsupported length (in excess of one diameter) formula (96), instead of giving values which are too high as predicted in Schiffbau, gives values which are too low by 50 per cent, even though the model is undoubtedly as irregular or even more irregular than the shorter lengths which are supposed to fail far below the theoretical value because of their irregularities. To get the correct collapsing pressure here, it would be necessary to multiply by a factor of 2 instead of 0.6. For shorter lengths of unsupported shell, (from 2.74" to 2.18"), a factor of 0.4 to 0.5 would appear to give the more reliable results, although it is quite certain that the proportional limit has been exceeded, in which case (96) is inapplicable.

It would seem, therefore, that formula (96) holds for only a comparatively short range within which a specific constant must be determined by experiment. This constant is likely a function rather of the <u>length</u> of unsupported shell than of the <u>thickness</u> of shell involved, assuming the same percentage accuracy in fabrication. Further tests are needed to determine the effect of unsupported length upon the constant required to make the actual collapsing pressure check with the theoretical.

It may or may not be significant that the constant 0.4 seems to give approximate collapsing pressures according to (96) even though the correct collapsing pressure is given directly by (92). If at the pressure at which failure occurs, the stresses are such that the modulus has changed from E within the proportional range to 0.4 E just before yield, then failure may be occurring by instability, and at the yield point the two formulae may merge into each other. This seems the more probable since the failure on all models appear identical in pattern whether the stresses calculated by (82) were above or below the proportional limit. This explanation, however, cannot account for a constant multiplier greater than unity in the longer models.

Table I shows also how values computed by formula (92) compare with experiment. The models ...75C, in which the frames were simply one turn of (.148" diameter) iron wire, give theoretical values which are considerably below the experimental, being as much as 47% and 48% below in the case of the shorter frame spacing. This is likely because the area of the frames is very great, although the theory pretends to hold for areas which approach infinity, (solid bulkhead). For all smaller frames, especially the channels, (92) gives very accurate values with a maximum deviation of 9 per cent for <u>all models tested and a mean deviation of less than 4 per cent</u>. This is undoubtedly as great as the accuracy with which the yield point of the material was determined. It must, however, be borne in mind that this formula has been checked for only a small range of values of frame spacing and scantlings, and that conclusions cannot be too readily formed as to its applicability under other combinations. The above variation for heavy frames would justify caution. Further tests should be made to determine the limits of applicability of the formula.

SCALE EFFECT

No scale effect is predicted by the theory and our results thus far seem to bear this out.

STRENGTH OF FRAMES

When a simple circular ring is subjected to uniform, external pressure, collapse occurs by instability and the generally accepted formula due to M. Levy (Jour.d.math. pure et appl., Liouville, Ser. 3 Vol. X, (1884) p.5) is

$$P_k = \frac{3\ EI}{r^3} \qquad [36]$$

where P_k is the pressure at which frame buckles,
E is Young's modulus,
I is the moment of inertia of cross-section of frame,
r is the radius of frame to neutral axis.

This formula is usually attributed to Foppl. In the 1900 edition of Foppl's "Festigkeitslehre" it is given in the slightly altered form:

$$P_k = \frac{4\ EI}{r^3}$$

Formula (36) can be extended to include the cylindrical tube of infinite length if the proper assumptions are made concerning the resistance to change of curvature caused by adjoining portions. When the value of I for a rectangular cross-section of unit length is taken, (I = 1/12 t.1) equation (36) becomes

$$P_k = \frac{E}{4} \frac{(t)^3}{r^3}$$

where t = thickness of frame measured radially, and if we take into consideration the resistance to the change of curvature offered by the adjoining portions, we get (see Bryan, Proc. Camb. Phil. Soc. Vol. VI, (1888) p. 287)

$$P_k = \frac{m^2}{m^2 - 1} \frac{E}{4} \frac{(t)^3}{(r)^3} = 66{,}700{,}000 \frac{(t)^3}{(d)^3}$$

where d = diameter of ring, and m = Poisson's ratio.

The empirical values obtained experimentally by Carman and Carr (Univ. Illinois Engr. Expt. Sta. Bull, No. 5, 1906) and Stewart (Am. Soc. Mech. Engrs., (1906) p. 795) are

$$P_k = 50{,}200{,}000 \frac{(t)^3}{(d)^3}$$

which is about 25 per cent lower, yet of identical form for variations of t and d. The decrease in actual collapsing pressure in the latter formula is attributed to irregularities in material and workmanship.

It seems, therefore, that if a tube fails by instability, the method of failure is identical with that of a frame or ring which fails by instability. If, then, the pressure on the shell is sufficient to cause its collapse by instability, while at the same time the load transmitted by the shell to the frame exceeds the frame's critical buckling pressure, the shell and the frame will both collapse at that pressure. However, if the frames are made stronger, the shell will collapse by bulging between them, after which the frames will receive the entire load. They will then collapse by instability if this total load exceeds their critical buckling pressure. Prof. Hovgaard (Memo. 83 to Bu. of C & R, p 2) says that "the formula applies when frames are fitted, provided they are of uniform construction and evenly spaced, in which case they may be assumed to form an integral part of the shell and their moment of inertia may be supposed to be evenly distributed, each frame being considered in conjunction with a length of one frame space of the shell plating". This statement, of course, has no bearing upon the case where the frames are so strong that the shell fails first by bulging. The frames then have the effect of shortening the tube and the collapsing pressure must be computed for a length of tub equivalent to the unsupported length between frames. . greater frame strength has no influence on the strength of the tube providing the spacing is sufficiently great to insure collapse by instability.

This was tested with models 6" in diameter and 14.5" long. (See data sheet No. 1, series II, 2 to 10 B1 and table II). It was found that a single turn of (.102" diameter) wire at the center of the model caused as high a collapsing pressure as a solid bulkhead at that point. The same results were obtained for models D = 6", L = 8.5".

TABLE II

Models 14.5" Long

Model SII	Frame	Collapsing Pressure Actual	Thickness	Pressure converted to standard t = .0250
2A	16 G., D = .050	36.9	.0238	40.9
5A2	12 G., D = .0795	38.2	.0250	38.2
3A	10 G., D = .102	51.1	.0245	53.2
4A	7 G., D = .1475	48.5	.0240	52.7
4B	7 G., D = .1475	55.1	.0252	54.0
10A	Bulkhead	46.3	.0230	55.2
10A1	"	48.9	.0230	58.6
10B1	"	48.9	.0240	53.2
10B	"	46.7	.0234	54.0
2X	16 G., D = .050	57.8	.0235	65.8
3X	10 G., D = .102	68.4	.0235	78.1
4X	7 G., D = .1475	72.0	.0240	78.4
10X	Bulkhead	69.8	.0236	78.4

STRENGTH OF ARCHES

The formula for collapse of circular frames can be extended to the collapse of pin-jointed arches; that is, to circular frames which are constrained to fail in more than two lobes. The actual development of the formula gives (See Applied Elasticity, Timoshenko and Lessells, p. 246)

$$P_k = \frac{(n^2 - 1)\ E\ I}{r^3} = \left[\left(\frac{2\pi}{\theta}\right)^2 - 1\right] \frac{E\ I}{r^3} \qquad [36']$$

where n is the number of lobes into which the frame collapses or $n = \frac{2\pi}{\theta}$.

When n = 2, which is the case for the free circular frame, we get formula (36) mentioned above. However, if the frame is held rigid at two points, leaving a free arch subtending an angle θ at the center of the frame, then the angle θ is fixed and we can use (36'). If the ends of the frame be considered fixed or encastre, by analogy to Euler's formula for beams with fixed ends, the length l considered for the pin-ended rod must be replaced by 2/3 l, since $l = r\theta$, θ must be replaced by 2/3 θ and (36') becomes

$$P_k = \left[\left(\frac{3\pi}{\theta}\right)^2 - 1\right] \frac{E\ I}{r^3} \qquad [36'']$$

For θ = 180, (36') gives the coefficient 3 which makes it identical with (36), but when substituted in (36'') the coefficient becomes 8. The values of the coefficient to be used for various angles are given in the table III below.

Table III

Values of Calculated Coefficient for Arches

Angle θ, degrees	Pin-jointed	Fixed ends
180	3	8
135	6.1	15
120	8	19.25
90	15	35
60	35	80

These values all assume, of course, that the proportional limit of the material has not been exceeded, and also that there is no eccentric loading due to local stresses transmitted to the frame by the shell in the process of collapse.

According to the above table, if a frame with an unsupported arc of 180 degrees fails due to instability by formula (36'), that same frame might easily be strong enough if only 135 degrees of arc were left unsupported. It frequently happens in submarine construction that the bottom of the strength hull is stiffened by rigid tank structures reaching up above the bilges and often above the axis of the vessel, leaving a relatively slender arch-like frame at the top. It is desirable, therefore, to know how much dependence can be placed on formula (36') in actual practice.

Accordingly, a series of five models were constructed with heavy floors which made the frames rigid for arcs of 90 degrees, 135 degrees, 180 degrees, 225 degrees, and 270 degrees. The frames were turned on the lathe and made to simulate the shipbuilding channel C-109 (6" x 3½" x 15.3 lbs.). They were computed by formula (36) to fail at 150 pounds pressure. They were first used in models SX, 154D50T99U1, 2,3. (See data sheet No. 3 and Table I). The computed buckling pressures by (92) were 172.4, 171.1, and 171.1 pounds, respectively, while the actual buckling pressures were 170, 165, and 155 pounds. The last named model had a variation in radius greater than that allowed, being about 0.020" in an arc of 30 degrees. In each of these models, the frames failed <u>with</u> the shell, as was to be expected, since by

(36) they were computed to fail at 150 pounds. These same frames were used in the series of five models. If the constant 3 in equation (36) changes to 6.1 for 135 degrees and to 15 for 90 degrees unsupported arc, the frames should surely be strong enough to hold even after the shell has failed completely. In the latter case, the frames should hold 2,250 pounds pressure, which, of course, is absurd since this load gives rise to stresses exceeding the yield point of the material. The models were tested with the results shown in Table IV.

TABLE IV

Unsupported arc	Collapsing pressure			
	Shell		Frame	
	Theory	Exp't	Theory	Exp't
360°	172.4	170	150	Failed
360°	171.1	165	"	with shell
270°	177.5	165	"	"
270°	183.1	180	"	"
225°	205.0	175	"	"
180°	200.7	160	"	"
135°	173.8	165	300	"
90°	188.3	185	2,250	"

It is seen that decreasing the length of unsupported arc of the frames does not noticeably affect their buckling pressure. This may be due to the fact that because of eccentric loading at the bulges, the flanges are bent out of shape and the frames fail by local crippling rather than through pure instability. Whatever the explanation, it is obvious that the constant in (36) cannot be increased with safety when applied to frames in a submarine hull

All that has been said for inside frames holds equally well for outside frames providing that by welding, or possibly by riveting, the frames become an integral part of the shell. Only one model has been tested with outside frames. These frames were made to the same scale from an I beam (B17 Am. Standard Section) with half of one outer flange removed. They were computed by (36) to fail at 209.1 pounds pressure and the shell by (92) to fail at 183.4 pounds. The frames were spot-welded to the shell at one-half inch intervals, staggered on the two sides of the flange. The first bulge appeared in the shell at 160 pounds pressure and we define this as the collapsing pressure of the model. However, it was possible to increase the pressure to 180 pounds without complete collapse. Many new bulges were formed, but the frames did not fail, although there were indications that the flanges were becoming bent out of shape. Due to leaking of the model, greater pressures could not be applied.

The behavior of this model was identical with the large model tested at the Portsmouth Navy Yard. This latter was 0.443 scale of a full sized submarine, or 86.6" outside diameter, and the scantlings were 5.379 scale of our 16.1 outside diameter model just mentioned. The Portsmouth model was much more irregular than the small models or the full-size ships. It is interesting to observe that, as the result of previous model tests, it was possible to predict the point of failure as well as the collapsing pressure. The first bulge occurred at 140 pounds pressure at the most irregular region. Three other bulges appeared at 150 pounds. At 165 pounds pressure, four other bulges appeared almost simultaneously and the leaking became so excessive that the test had to be discontinued. There is, however, one notable difference between the Portsmouth model and our own. While our model had a shell whose yield point was 32,000 pounds per square inch and formula (92) was determinative, the larger model was made of material with a yield point of 36,000 pounds per square inch and by (82) the stress was still within the proportional limit. The failing pressure was predicted correctly by (96) when r was used equal to the radius of curvature of the flattened portion at which failure first occurred and the answer was multiplied by 0.6 according to the rule given in Schiffbau. However, because of the eccentric loading at the flattened portion, the stresses are likely much higher than given by (82), and may easily be at or near the yield point of the material.

Comparison of these two models gives no indication so far that there is any scale effect and shows that 16" models can be relied upon to give reliable results as long as the scantlings can be made to duplicate the scantlings of the larger models in geometrical forms. However, material of identical physical properties must be used.

NUMBER OF FRAMES

When designing models for testing, the question at once arises as to the effect of the length of the model. Will the collapsing pressure be the same for a model containing two or three frames as for a model of the same scantlings containing twelve or fifteen frames? The number of frames does not appear in either (92) or (96) and the assumption is that they are unimportant as long as the frame spacing remains constant. To test this, a model (S IV 149D 50T 75C) 38.7" long was constructed, containing 16 wire frames. It failed at 125 pounds pressure. After the failed portion was cut away, we had left a model 10" long, containing 4 frames. This, when tested, failed at 127 pounds pressure. The measured thickness for the shorter model was 0.0488" as compared with 0.0485" for the longer model, hence it should have failed at slightly higher pressure. This shows that a model containing three or four frames can be relied upon to give as reliable results as a model with a larger number of frames. One precaution, however, is necessary. Since the heads of the models are bulkheads, or frames of infinite strength, the shell by (92) is weakest at the end spaces. To rule out the effect of these bulkheads, the end spaces must be made shorter, thus forcing the shell to fail between the frames. In all our models after S III 154F, the end spaces were made about two-thirds of the frame spacing.

EFFECT OF LONGITUDINAL STRAPS

An investigation was made to determine the effect of longitudinal straps (equivalent to two thicknesses of shell) on lobe formation. It has always been felt that if the shell were strengthened by longitudinal straps, such as seam straps, the lobes, or bulges, would be hindered in their regular formation, their length would thereby be decreased and, therefore, by (96), the collapsing pressure would be considerably increased. This was the same assumption which made it seem reasonable to expect that frames would be strengthened by decreasing the length of unsupported arc.

Tests were made with models 6" in diameter. We believed these models to be fairly accurate, but no method was then available for determining the actual contour of the surface. In the first model, (SII, 1E), solder only was used at the seam. In the other models, (SII, 1G-9N, see data sheet No. 1 and Table V), the seam was not only soldered but was supported by a butt-strap in addition. These straps had the following widths: 1/4", 1", 2", 4", 6", 9 1/2" (semi-circumference), 12 1/2" (2/3 circumference), 14 1/2" (3/4 circumference), and 17" (.895 circumference). While there was likely some additional strength due to the longitudinals taking the end load, there was no marked increase in collapsing pressure when proper corrections were made for variations in shell thickness. It is certain that these models, which had 14.5" of unsupported shell length, failed by instability. Formula (96) gives the collapsing pressure as 36.7 pounds for a shell thickness 0.025", and the number of lobes as 4. This means that each lobe should be 4.71" long. For a lobe length less this value, - that is, for a greater number of lobes, the collapsing pressure by (96) would be increased. The length of shell unsupported by the butt-strap in 9N was 1.85" and this should represent the maximum length of lobe. Since the circumference was 18.85", n would equal 10 and the collapsing pressure by (96) would be 200 pounds. This value, however, is more than 500 per cent greater than the actual collapsing pressure. (See Table V). The collapsing pressure of 9N is 16 per cent above the mean, but 1B failed at a still higher pressure and it had only a 1" butt-strap. Likely 9N and 1B were more nearly circular and therefore failed at the theoretical collapsing pressure, while models 1E, 5A1, 8A, and 8B were more irregular which caused their lower collapsing pressures. This is even more probable when we consider that 1E, which had solder only at the seam, failed at a higher pressure than 8A and 8B which had straps equal to a semi-circumference. We must conclude, then, that the collapsing pressure cannot be materially increased by using longitudinals to break up the lobe formation. However, we cannot be too certain of this when the unsupported length of shell is less than the length of one lobe, since the one model in which this condition existed may have been defective. Further tests are contemplated with larger and more accurate models, in which the longitudinals will simulate those used in submarine construction.

TABLE V

Effect of Longitudinal Straps

Model SI-	Seam support	Failing P. lbs.	Shell Thickness	P converted to t =.0250
1E	Solder only	30.2	.0251	29.8
1G	1/4" strap	28.4	.0236	32.1
1A	1" strap	32.9	.0252	32.1
1B	1" strap	38.7	.0248	39.3
5A1	2" strap	29.8	.0255	28.5
6A	4" strap	34.7	.0250	34.7
7A	6" strap	34.7	.0253	36.8
8A	9½ " strap	25.8	.0235	29.6
8B	" " strap	26.7	.0242	28.5
9A	12½" strap	34.7	.0250	34.7
9G	14½" strap	32.0	.0243	33.9
9N	17 " strap	36.5	.0243	38.8

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CLASSIFICATION OF MODELS AND IDENTIFICATION NUMBERS

<u>Classification:</u>

Series	Description
I	6 inch models (internal diameter = 6 in.).
II	Plain. One inter-frame space.
III	16 inch models with an open head in nearly all cases and one inter-frame space determined either by two heavy frames near the ends or, as in a few early models, by the ends themselves. ("Inter-frame" refers to the unsupported shell between two adjacent frames or bulkheads).
III-L	Same as Series III except for the use of lap seams instead of butt seams.
IV	16 inch models, closed heads. Many frames. 38.7" long.
V	16 inch models, closed heads. Many frames. 15 in.long.
VI	6 inch models. Many frames. 14.5 inch long.
VII	6 inch models. 5 frames, 4 inter-frame spaces.
VIII	Portions of models of Series IV.
IX	6 inch models. 5 outside wire frames, 4 inter-frame spaces.
X	16 inch models, open heads. Two inter-frame spaces determined by three inside frames.
XI	6 inch models. 3 frames, 2 inter-frame spaces.
XII	16 inch models, open heads. Two inter-frame spaces determined by three outside frames.
XIII	6 inch models. 2 frames, 1 inter-frame space.

<u>Identification Numbers:</u>

The system used, discussed on page 8 of the report, is best described by an example. The identification number

S III 546 D 50 T 1

signifies:

(a) Series III of the above classification.
(b) Unsupported length (distance between the inner surfaces of two adjacent frames or bulkheads) is 0.546 times the internal diameter.
(c) Nominal thickness is 0.050 inches.
(d) The model is first of a group of identical models.

U.S. E.M.B. Report No. 262 (Supplement) Sheet 2

In some other identification numbers there were additional symbols inserted after "T". They are described in the following examples:

In S X 149 D 50 T 51 C 3 the 51 C signifies that the depth of frame is 5.1 times the nominal shell thickness, and that the frame is of circular cross section. The symbols for frames of other cross sections are

U Channel.

I I-beam.

L Angle.

I I-beam with half of outer flange removed.

In S X 154 D 50 T 99 UF 135 C 1 the latter part signifies that the depth of the channel frame is 9.9 times the nominal shell thickness, and a flat of 135° circumferential extension is attached to the frame. The usual flat is a circular sector; the "C" after 135 signifies that this particular flat was a piece of a circular ring.

In S XII 154 D 50 T 111 I 6 LKT 1 the 6 LKT signifies 6 longitudinal straps, a keel, and a tank top.

Model Pressure Vessels

CLASSIFICATION

Revised July 1933

Type I All 6 in. models (internal diameter = 6 in.)

II 16 in. models with closed heads.

III 16 in. models with open heads and one inter-frame space determined by two heavy frames near the ends. ("Inter-frame space" refers to the unsupported shell between two adjacent frames or bulkheads).

IV 16 in. models with open heads and two interframe spaces determined by three inside frames.

V 16 in. models with open heads and two inter-frame spaces determined by three outside frames.

VI 16 in. models with open heads and two inter-frame spaces determined by two pairs of frames of unequal size.

<u>Subgroups</u>

III-L Models of Type III with lap seams instead of the usual butt seams.

IV-F Models of Type IV with flats attached to the frames.

V-S Models of Type V with special features of a submarine pressure hull.

<u>Comparison of Revised and Previous Classifications</u>

Note: The previous classification of models by "Series" is described in a supplement to U.S. E.M.B. Report No. 262, June, 1930.

Type I comprises all of the seven previous Series: I, II, VI, VII, IX, XI, XIII.

Type II comprises the previous Series: IV, V, VIII, part of III.

Type III comprises practically all of the previous Series III; Type III-L corresponds to the previous Series III-L.

Type IV corresponds to the previous Series X.

Type V corresponds to the previous Series XII.

Collapse of Submarine Models   Data Sheet No 1

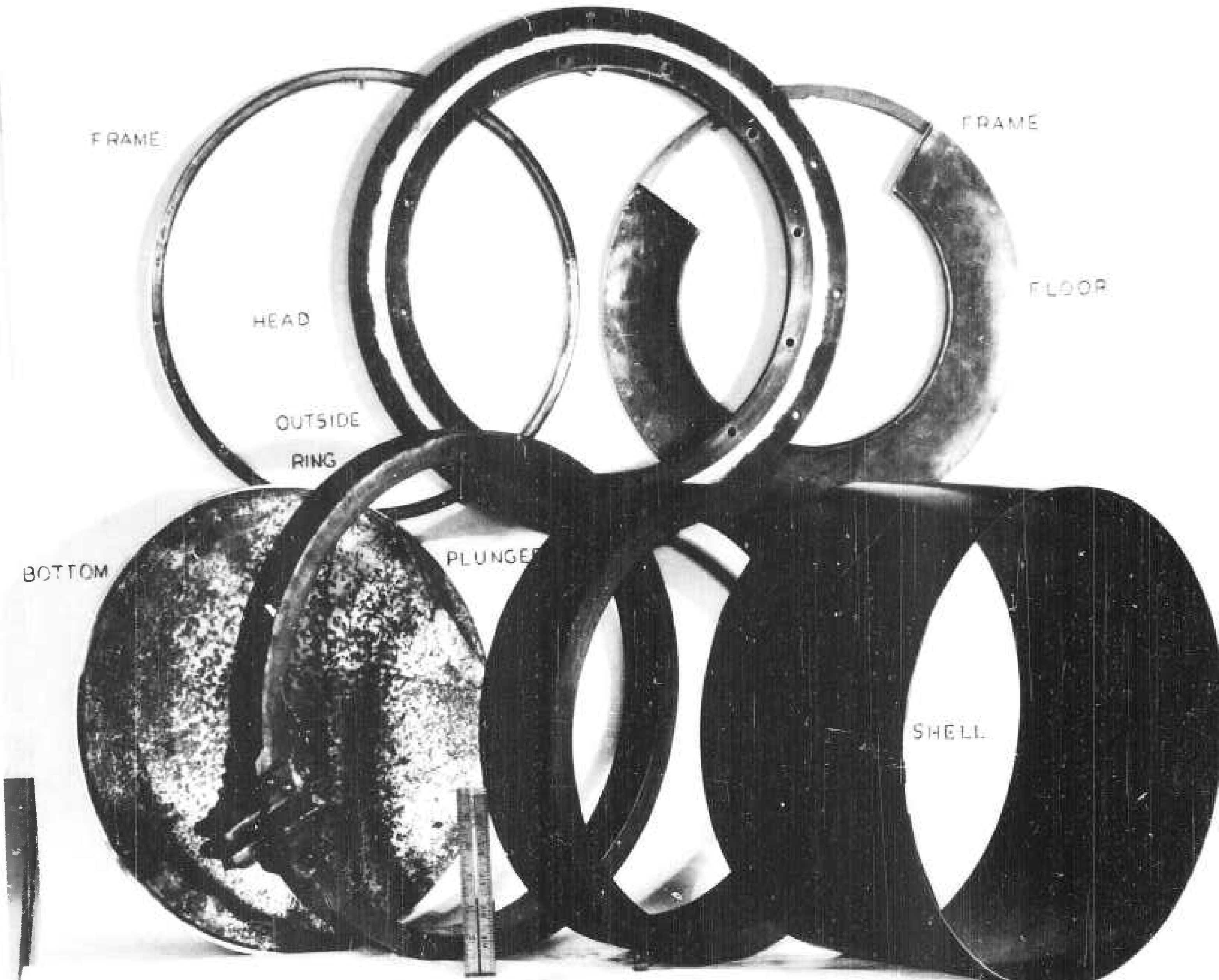
Number	Description	Inside L	Inside D	L/D	Wall Thickness	T/D	D/T	Actual Failing Pressure Feet	Actual Failing Pressure Lbs	Remarks
Series I #1	Plain	8.5"	6"	1.41	.0347	.00578	173.0	176	78.2	Series I #1 to #8 Had
#2	"	14.5"	"	2.42	.0356	.00594	168.5	156	69.4	Lap Joints Lap ½"
3	Bulkhead	8.5"	"	1.41	.0315	.00525	190.4	175	78.0	Riveted at Intervals
4	"	14.5"	"	2.42	.0345	.00575	174.0	132	58.7	and Soldered
5	Plain, 3 Longitudinal Stiff-	8.5"	"	1.41	.0353	.00588	170.0	335	148.9	
6A	eners, one over Seam	14.5"	"	2.42	.0349	.00582	172.0	220	97.8	All Failures on or
6B	" 1"·1"·⅛" L	"	"	"	.0348	.00580	172.4	195	86.7	near Seam, due to
6C	"	"	"	"	.0250	.00417	240.0	87	38.7	Out-of-Roundness at
6D	"	"	"	"	.0250	.00417	240.0	95	42.2	Lap
7	Bulkheads, 3 Longitud-	8.5"	"	1.41	.0322	.00537	186.4	259	115.0	
8	inal Stiffeners	14.5"	"	2.42	.0336	.00560	178.5	208	92.9	
9A	Butt Joints, Plain, one	"	"	"	.0247	.00412	243.0	80	35.6	Failed Away From Seam.
9B	Stiffener on Seam	"	"	"	.0342	.00570	175.4	180	80.0	
	Series II					All Have Butt Joints				No Rivets Used
* 1E	Solder only on Seam,	14.5	6	2.42	.0251	.00419	239.0	68	30.2	Failed Away From Seam
1F	No Strap	"	"	"	.0248	.00414	242.0	59	26.2	Failed at Seam - Not Thinnest Region
1G	¼" Strap Down Seam	"	"	"	.0236	.00393	254.2	64	28.4	
1A	1" " " "	"	"	"	.0252	.00420	238.2	74	32.9	
1B	" " " "	"	"	"	.0248	.00414	242.0	87	38.7	
5A1	2" " " "	"	"	"	.0255	.00425	235.3	67	29.8	
6A	4" " " "	"	"	"	.0250	.00417	240.0	78	34.7	
7A	6" " " "	"	"	"	.0253	.00422	237.2	78	34.7	
8A	7½" " or Semi-Circum.	"	"	"	.0235	.00392	255.3	58	25.8	Irregular from Rolls
8B	" " " "	"	"	"	.0242	.00403	248.0	60	26.7	
9A	12½" or ⅔ Circumference	"	"	"	.0250	.00417	240.0	78	34.7	
9G	14½" " ¾ "	"	"	"	.0243	.00405	247.0	72	32.0	
9H	17" " .895 "	"	"	"	.0243	.00405	247.0	82	36.5	
2A	16 Gauge Wire, Diam .050"	"	"	"	.0238	.00397	252.0	83	36.9	One Loop of Spring
3A	10 " " " .102"	"	"	"	.0245	.00408	245.0	115	51.1	Steel Wire Midway
4A	7 " " " .1475"	"	"	"	.0240	.00400	250.0	109	48.5	Between Heads
4B	" " " " "	"	"	"	.0252	.00420	238.0	124	55.1	
5A2	12 " " " [illegible]	"	"	"	.0250	.00417	240.0	86	38.2	
10A	Bulkhead in Center	"	"	"	.0230	.00383	261.0	104	46.3	Did not Fail at Thinnest Region
10A1	Lower Half of 10A	7.25		1.21	.0230	.00383	261.0	110	48.9	Failed Without Warning
10B	Bulkhead in Center	14.5		2.42	.0234	.00390	256.5	105	46.7	10A + 10A1 Both Failed in Seam
10B1	Upper Half of 10B	7.25		1.21	.0240	.00400	250.0	110	48.9	Metal Strained Past Bulkhead

Collapse of Submarine Models   Data Sheet No. 2

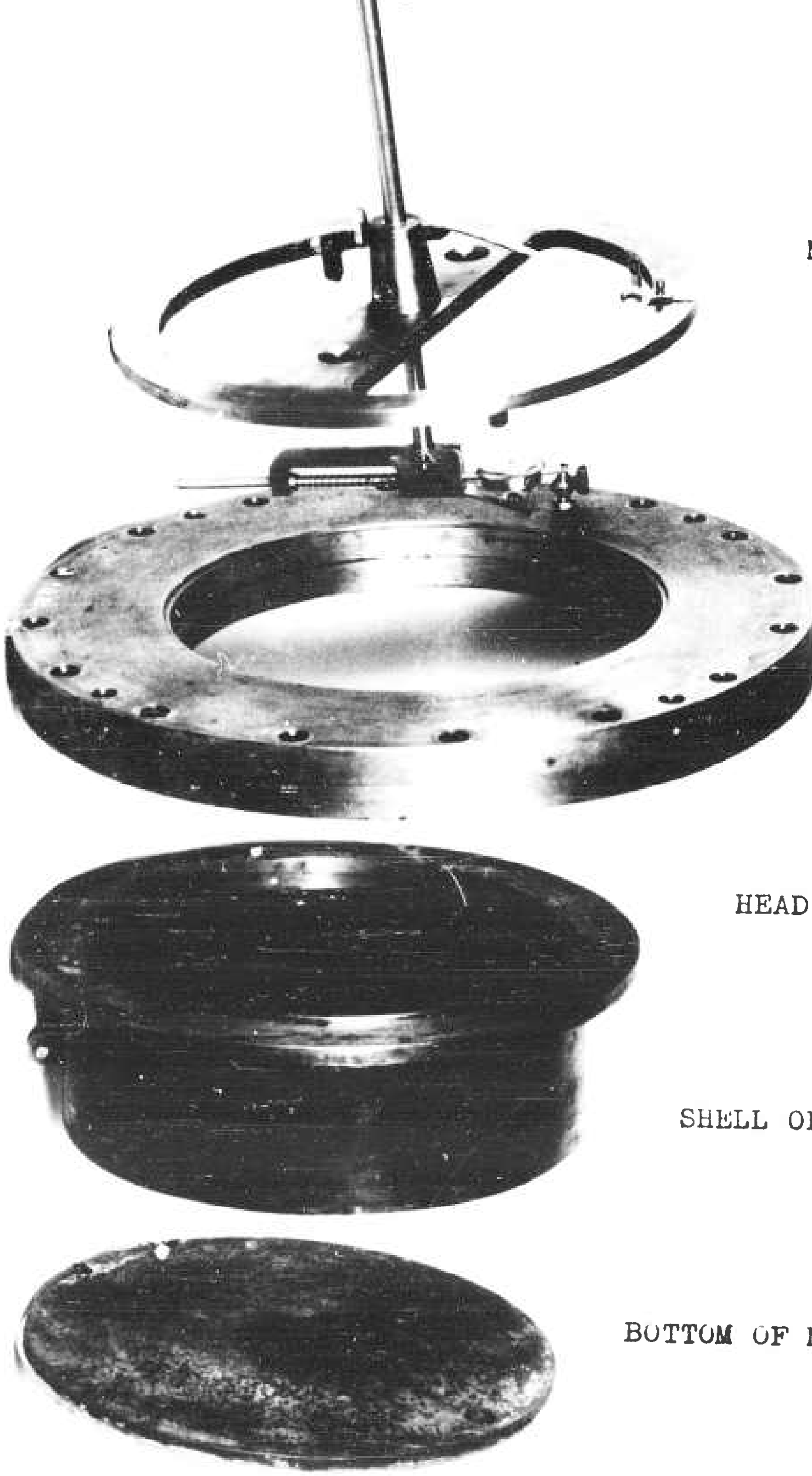
Number	Description	Inside L	Inside D	L/D	Wall Thickness	T/D	D/T	Actual Failing Pressure Feet	Actual Failing Pressure Lbs	Remarks
	Series II Continued									
SII. 1H	3 Strips ½"x½" Across the Butt	14.5	6	2.42	.0243	.00405	246.8	52	23.1	
1I	" " "	"	"	"	.0235	.00392	255.3	61	27.1	Impossible to get
1J	5 " " "	"	"	"	.0245	.00409	245.0	78	34.7	Reliable Models by
1K	9 " "	"	"	"	.0233	.00389	257.5	55	24.4	This Method
1X	Plain, 1" Strap Down Seam	8.5"	"	1.41	.0236	.00394	254.2	102	45.3	
1Y	" " "	"	"	"	.0233	.00389	257.5	98	43.6	
1Z	" " "	"	"	"	.0385	.00575	174.0	223	99.1	
2X	16 Gauge Wire Diam .050	"	"	"	.0235	.00392	255.2	130	57.8	Did not fail at flat place
3X	10 " " " .102	"	"	"	.0235	.00392	255.2	154	68.4	Predicted region of failure
4X	7 " " " .1875	"	"	"	.0240	.00400	250.0	162	72.0	One loop of spring steel
10X	Bulkhead in center	"	"	"	.0236	.00394	254.2	157	69.8	Wire midway between heads
11A	Plain, 4" Strap on Seam	14.5"	"	2.42	.0526	.00877	114.0	286	127	Future models in
11B	" " "	"	"	"	.0503	.00839	119.2	326	145	Series II have strap
12A	" " "	"	"	"	.0635	.01058	94.5	689	306	4" wide unless otherwise
										noted
3A	10 Gauge Wire Diam .102"	14.5	"	2.42	.0245	.00408	245.0	128	51.9	
33A	3 Loops 10 G Wire (Steel)	"	"	"	.0248	.00413	242.0	136	60.5	In all these models, frames
53A	5 " " "	"	"	"	.0243	.00405	246.7	149	66.2	were not soldered all
53B	" " " "	"	"	"	.0260	.00433	230.8	173	76.9	around, but were spotted
73A	7 " " "	"	"	"	.0248	.00413	242.0	151	67.1	at 90° intervals; spots
93A	9 " " "	"	"	"	.0250	.00417	240.0	216	96.0	about ½" long
33C	3 Loops 10 G Steel Wire	"	"	"	.0262	.00437	229.0	214	95.1	In future models, wires
33D	" " " Diam [illegible]	"		"	.0233	.00388	257.5	180	80.0	soldered all around.
53C	5 " " "	"	"	"	.0235	.00392	255.3	268	119	These soldered on one
93C	9 " " "	"	"	"	.0255	.00425	235.2	416	185	side only
153C	15 " " "	"	"	"	.0260	.00433	230.7	558	248	
54C	5 " 7 G " Diam [illegible]	"	"	"	.0253	.00422	237.0	398	177	
94C	9 " " "	"	"	"	.0253	.00422	237.0	448	199	
154E	15 " " Soft Iron	"	"	"	.0244	.00407	245.7	495	220	Frames failed
154C	" " " Spring Steel	"	"	"	.0248	.00413	242.0	529	235	
174C	17 " " "	"	"	"	.0250	.00417	240.0	567	252	
154C2	5 " " "	9.6"	"	"	.0236	.00394	253.2	540	240	End spaces ½" long
										End spaces made shorter
										in all future models

COLLAPSE OF SUBMARINE MODELS DATA SHEET NO. 3

SERIAL NUMBER	FAILING PRESSURE POUNDS EXPT	92 YIELD	96 INST.	LOBES EXPT LENGTH MAX.	MIN.	COMPUTED NO.	LENGTH	INSIDE DIMENSIONS L	D	T	YIELD POINT	FRAMES SPACING ℓ'	ℓ	SHAPE	DIMENSIONS	AREA	FLANGE b	FAILING PRESSURE	REMARKS
SIII 1	43	—	604	5.87	5.87	5	1005	22.67	16"	.0650	—	—	22.67	—	N O N E			—	
SII 2	138	—	781	9.00	6.44	6	838	16.0	"	.0625	—	—	16.0			"			
SIII 6A	49	—	323	8.25	8.25	4	1257	38.7	"	.0633	—	—	38.7			"			
SIII 6B	60	—	314	2.50	2.50	4	1257	38.7	"	.0625	—	—	38.7			"			
SIII 6C	62	—	301	7.50	7.50	4	1257	38.7	"	.0615	—	—	38.7			"			
SIII 153E	190	—	6211	6.31	6.00	14	3.59	38.7	"	.0608	—	24.17	22.92	O	D=.250	.0524	.125"	28.2	Frames failed
SIII 154F	219	—	6315	4.34	2.69	14	3.59	38.7	"	.0612	—	"	22.29	"	D=.375	.1186	.1875	1230	
SIV 179D50T75C	114	944	292	3.37	1.75	15	3.35	38.7	"	.0495	23,100	28.64	26.76	"	.375	"	"	971	End spaces shorter in future models
SV 179D50T75C	96	872	218	3.50	2.5	15	3.35	15	"	.0442	25,000	"	"	"	"	"	"	943	
SIV 149D50T75C	125	850	350	3.87	2.44	16	3.14	38.7	"	.0485	22,000	23.84	21.96	"	"	"	"	1158	
SVII 149D50T75C	127	856	355	5.03	1.81	16	3.14	10	"	.0488	22,000	"	"	"	"	"	"	1160	Part of SIV 149D50T75C
SV 149D50T75C	110	829	256	3.25	1.37	16	3.14	13	"	.0430	25,000	"	"	"	"	"	"	1125	
SV 179D50T51C	122	1291	240	3.75	3.06	15	3.35	14.12	"	.0463	28,600	28.64	22.39	"	.250	.1524	.125	21.0	Frames failed
SV 149D50T51C	115	1108	272	3.63	2.17	16	3.14	12.12	"	.0444	26,000	23.84	22.59	"	.250	.0524	.125	24.8	
		SERIES X					OPEN		HEAD			THREE		FRAMES					
SX149D50T51C1	115	1179	290	3.00	2.16	16	3.14	8.37	16"	.0455	24,000	23.84	22.59	O	.250	.0524	.125	25.1	Frames failed Shell irregular
SX149D50T51C2	162	1589	386	3.07	1.95	15	3.35	"	"	.0510	31,000	"	"	"	"	"	"	26.3	Frames failed Furniture steel in future mod.
SX149D50T51C3	170	1606	394	"	"	15	"	"	"	.0514	31,000	"	"	"	"	"	"	26.4	
SX179D50T75C	150	1299	316	"	"	15	"	"	"	.0510	31,000	28.64	26.76	"	.375	.1186	.1875	97.8	
SX154D50T50C1	180	1670	379	2.23	"	15	"	8.75	"	.0516	32,000	24.73	23.48	"	.250	.0524	.125	25.5	Frames failed at joint
SX154D50T50C2	170	1644	370	"	"	15	"	"	"	.0510	32,000	"	"	"	"	"	"	25.5	
SX154D50T99U1	170	1724	343	3.63	2.37	16	3.14	"	"	.0480	29,200	"	21.85	U	1.494	.0326	.288	1498	Frames failed
SX154D50T99U2	165	1711	339	2.79	2.79	16	"	"	"	.0478	29,200	"	"	U	1.288	"	"	1498	" "
SX154D50T99U3	155	1711	339	3.07	3.07	16	"	"	"	.0478	29,200	"	"	U	1.028	"	"	1498	" "
			MODELS	WITH	FLOORS		ATTACHED			TO	FRAMES								
SX154D50T99UF90	165	1775	362	3.63	3.63	16	3.14	8.75	16"	.0490	29,200	24.73	21.85	U	C 109 reduced	.0326	.288	1498	Frames failed
SX154D50T99UF90C1	180	1831	381.1	3.91	3.17	"	"	"	"	.0480	29,200	"	"	"	"	"	"	"	" "
SX154D50T99UF135C1	175	2050	375	3.84	3.56	"	"	"	"	.0497	33,000	"	"	"	"	"	"	"	" "
SX154D50T99UF180C1	160	2007	362	3.91	2.65	"	"	"	"	.0490	33,000	"	"	"	"	"	"	"	" "
SX154D50T99UF225C1	165	1738	326	3.38	3.38	"	"	"	"	.0474	30,000	"	"	"	"	"	"	"	" "
SX154D50T99UF270C1	185	1883	381	3.88	3.88	"	"	"	"	.050	30,000	"	"	"	"	"	"	"	" "
SXII 154D50T81I1	160	1834	407	3.35	2.65	16	3.14	8.75	"	.0497	32,000	24.73	20.39	I	"B17"	.0465	4.34	2091	
SIII 546D50T1	65	—	721	5.88	5.38	9	5.59	"	"	.0476	32,000	—	8.75	O	.375	.1186	.1875	—	
SIII 375D50T1	107	—	1288	4.61	4.19	11	4.57	"	"	.0510	—	—	6.00	"	"	"	"	—	



PARTS FOR FABRICATING MODELS



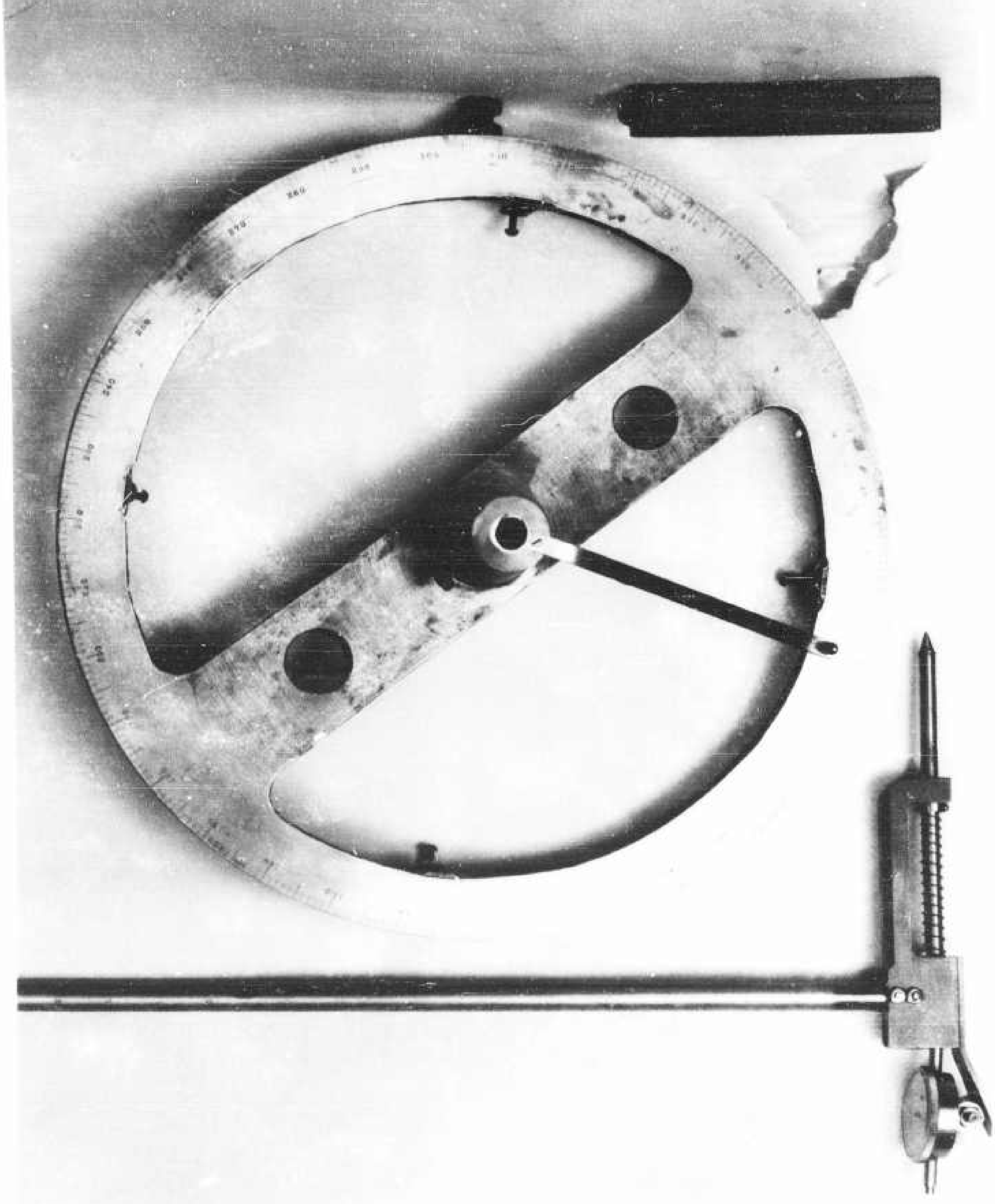
MEASURING
APPARATUS

HEAD FOR
COMPRESSION
TANK.

HEAD FOR MODEL

SHELL OF MODEL

BOTTOM OF MODEL



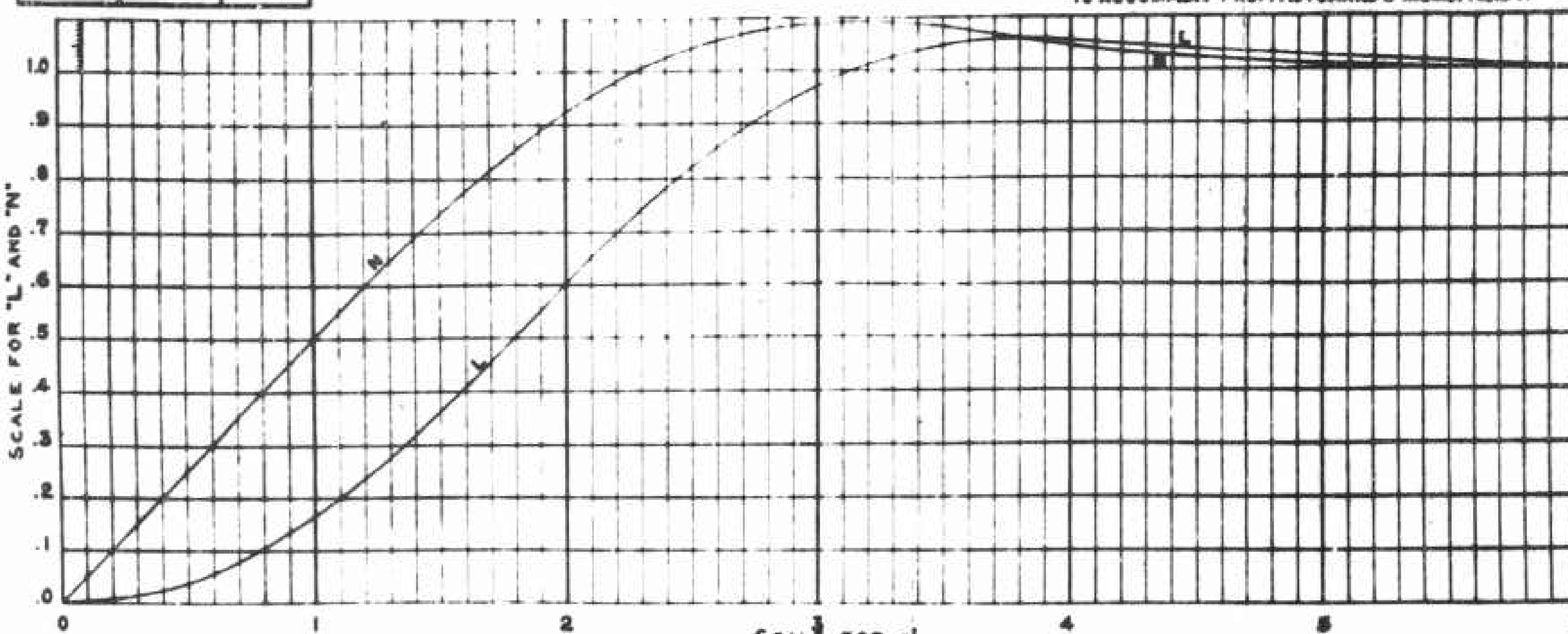
SUBMARINE STRENGTH CALCULATIONS.

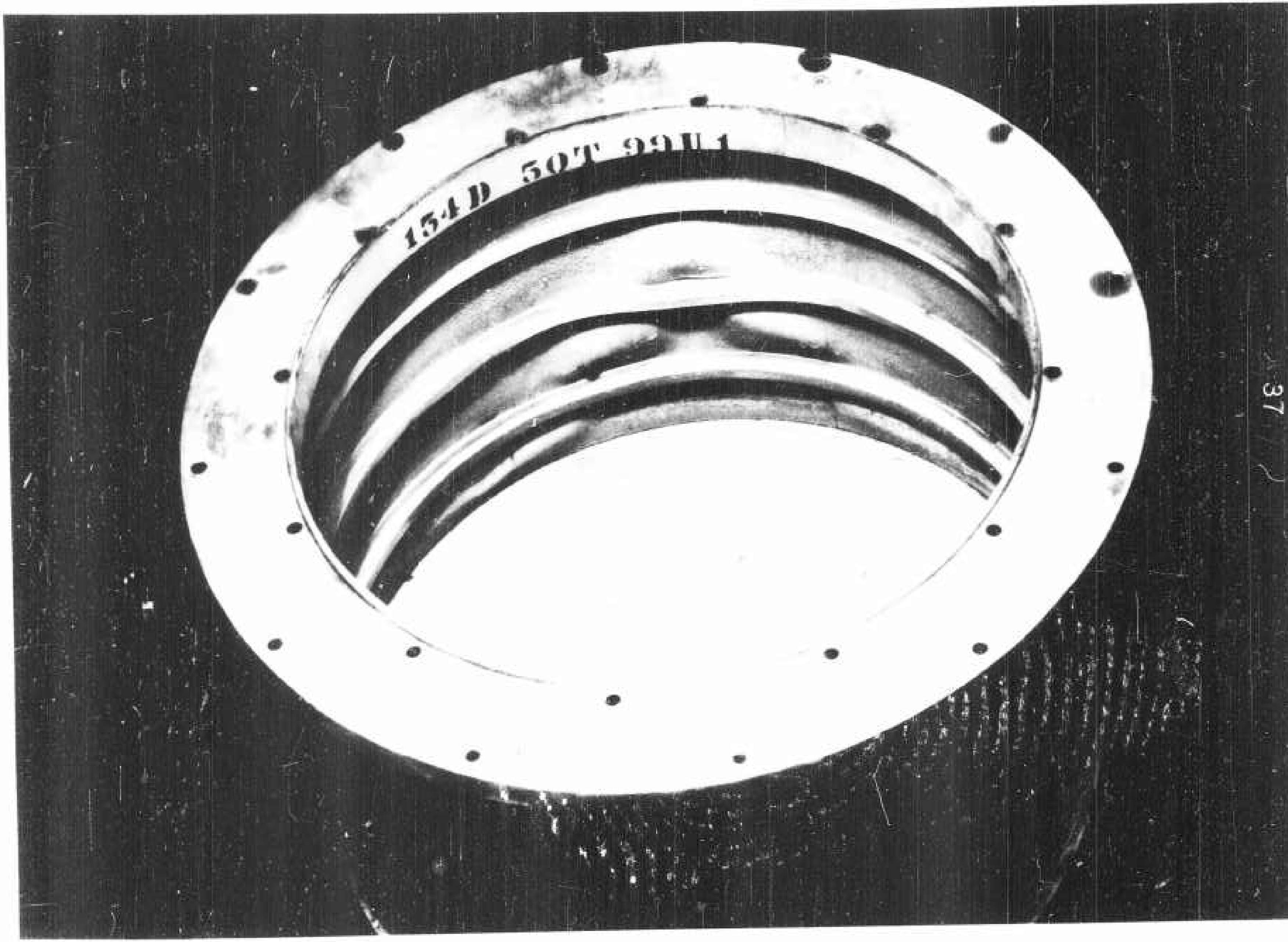
AUXILIARY QUANTITIES "L" AND "N".

$$\frac{\sinh al - \sin al}{\sinh al + \sin al} = L \quad \text{AND} \quad \frac{\cosh al - \cos al}{\sinh al + \sin al} = N$$

al IN CIRCULAR MEASURE	L	N
0	0	0
0.2	0.0066	0.100
0.4	0.0266	0.200
0.6	0.0601	0.300
0.8	0.1065	0.400
1.0	0.1670	0.500
1.2	0.2370	0.596
1.4	0.3170	0.680
1.6	0.4080	0.775
1.8	0.5030	0.855
2.0	0.6000	0.925
2.5	0.8220	1.045
3.0	0.9770	1.090
3.5	1.0506	1.083
4.0	1.0590	1.056
4.5	1.0400	1.027
5.0	1.0300	1.008
5.5	1.0134	1.002
6.0	1.0028	0.997

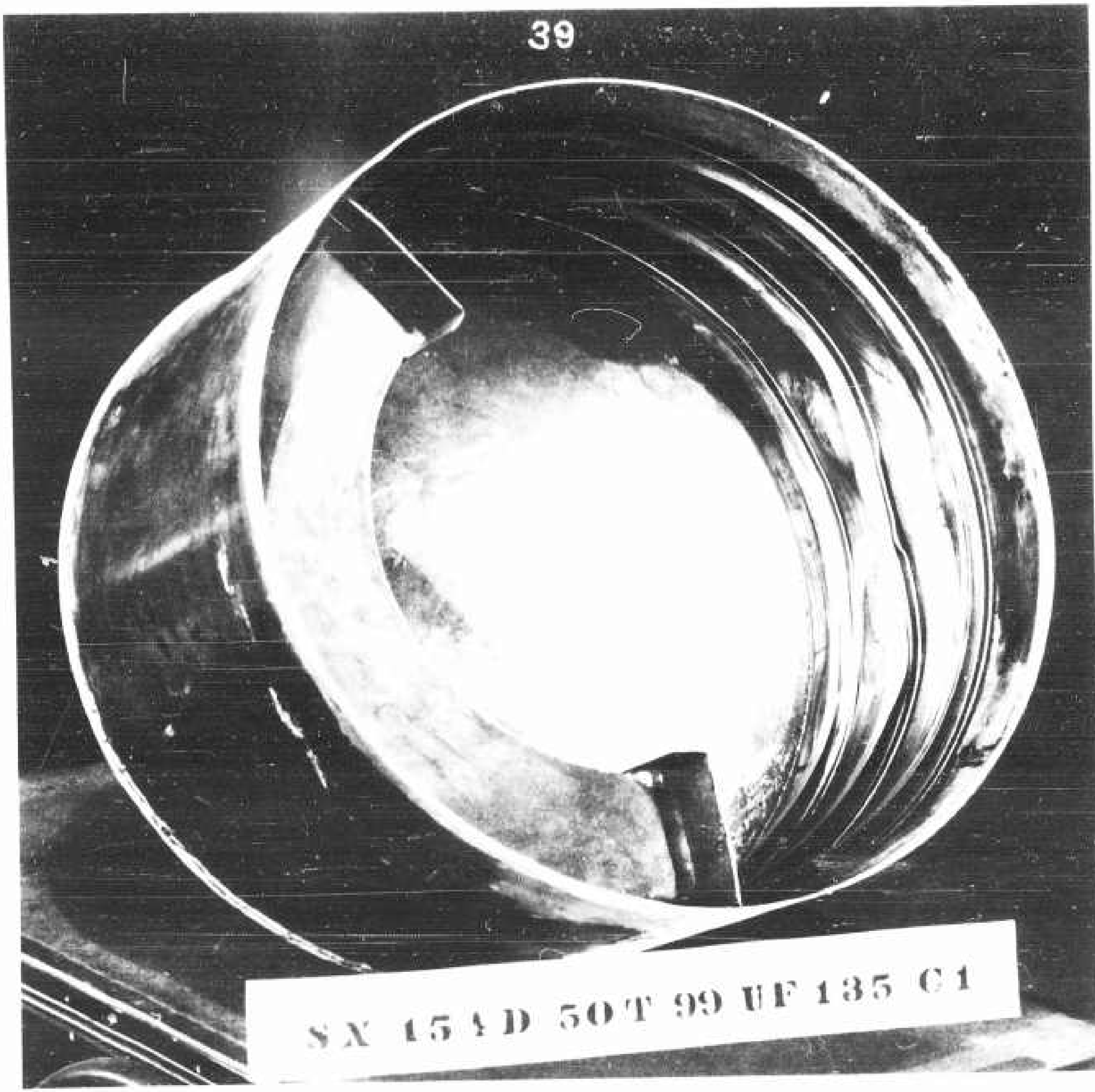
To accompany Prof. Hovgaard's Memo. No. 84.

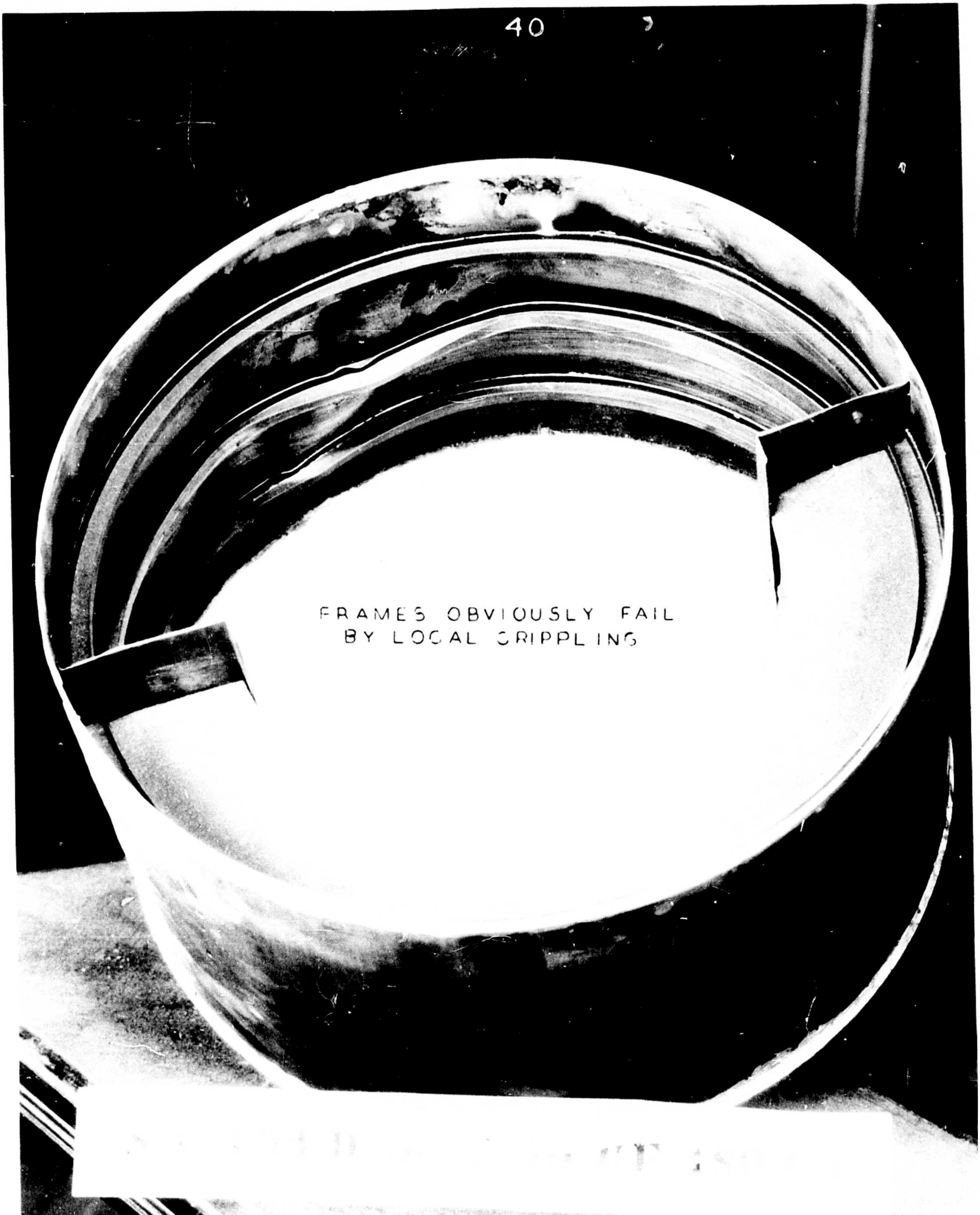




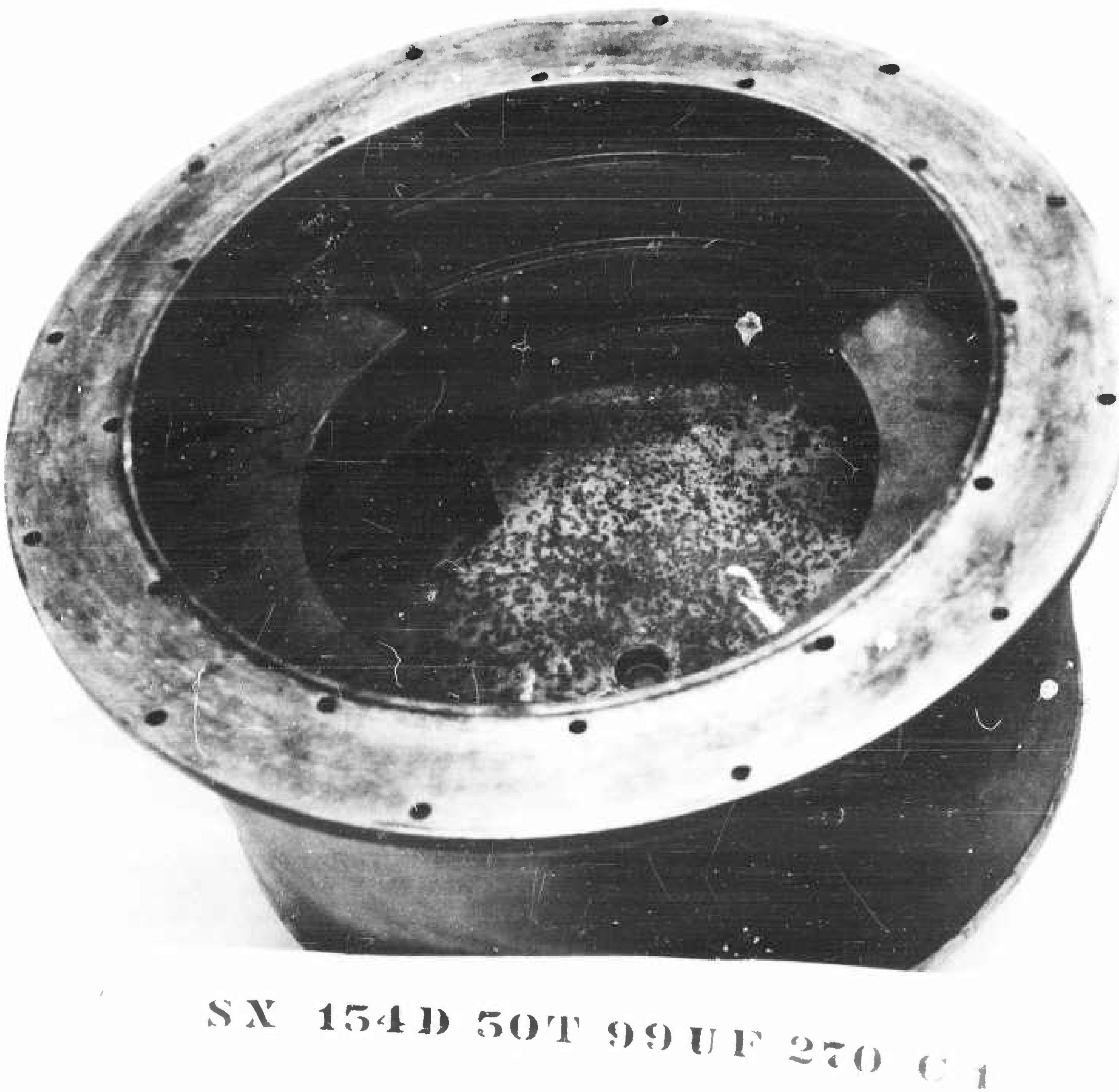
TYPICAL FAILURE OF MODEL WITH INSIDE CHANNEL FRAMES.
(NOTE THAT FAILURE OF FRAMES IS LOCAL AND IS APPARENTLY
DUE TO BULGING OF SHELL IN VICINITY.)


38

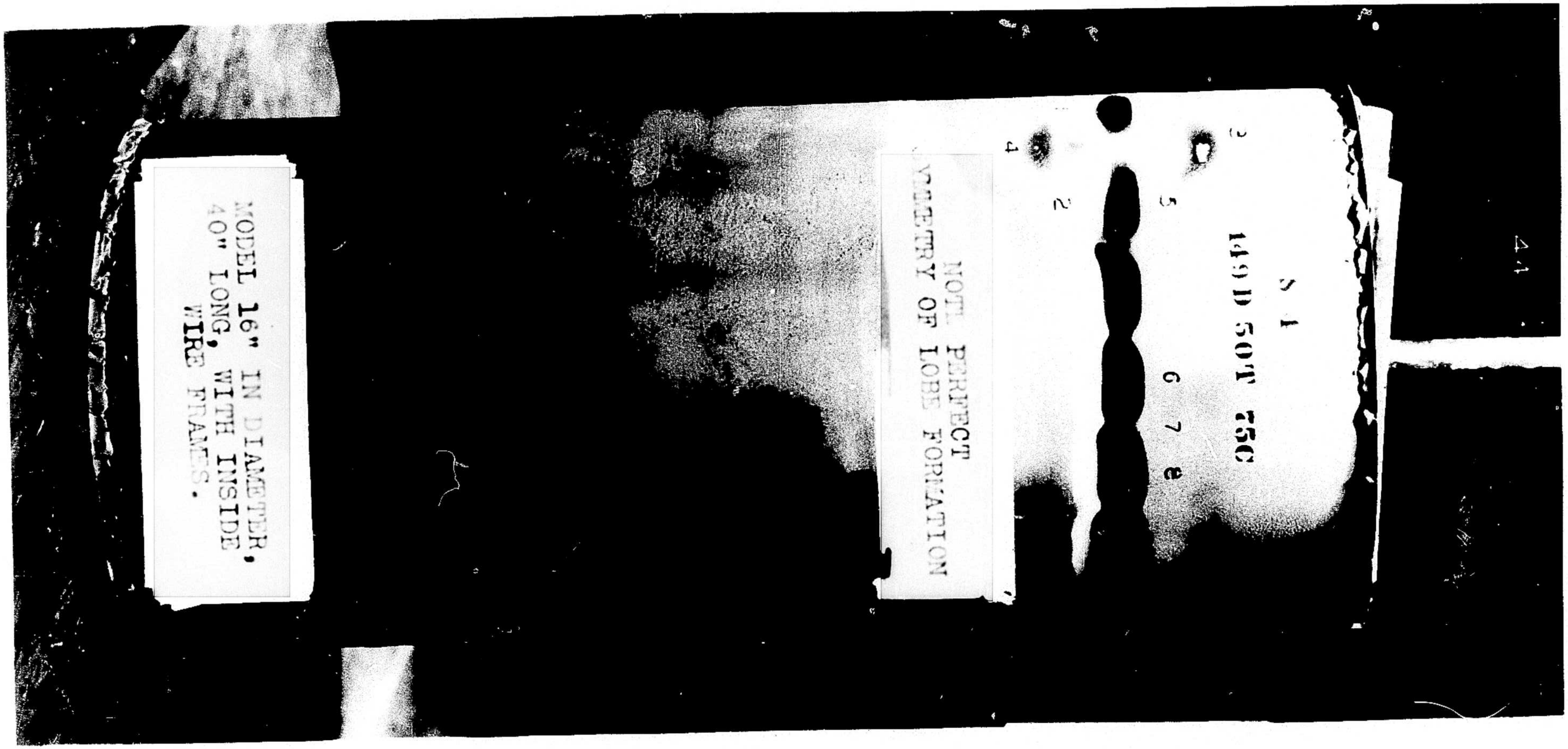

39
SX 154D 50T 99 UF 135 C1


FRAMES OBVIOUSLY FAIL
BY LOCAL CRIPPLING

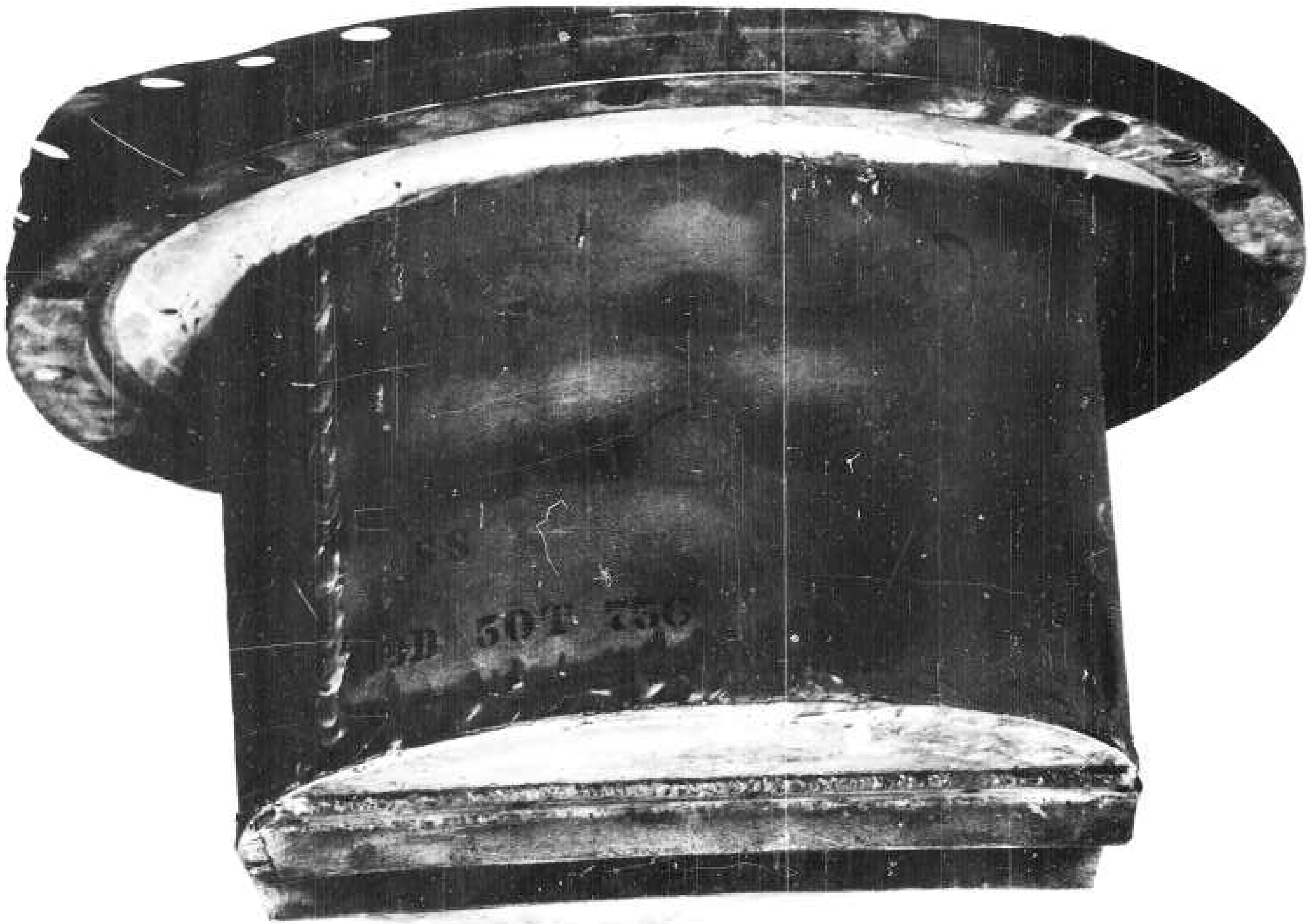
SX 154D 50T 99U F 225 C 1


SX 154D 50T 99UF 270 C 1

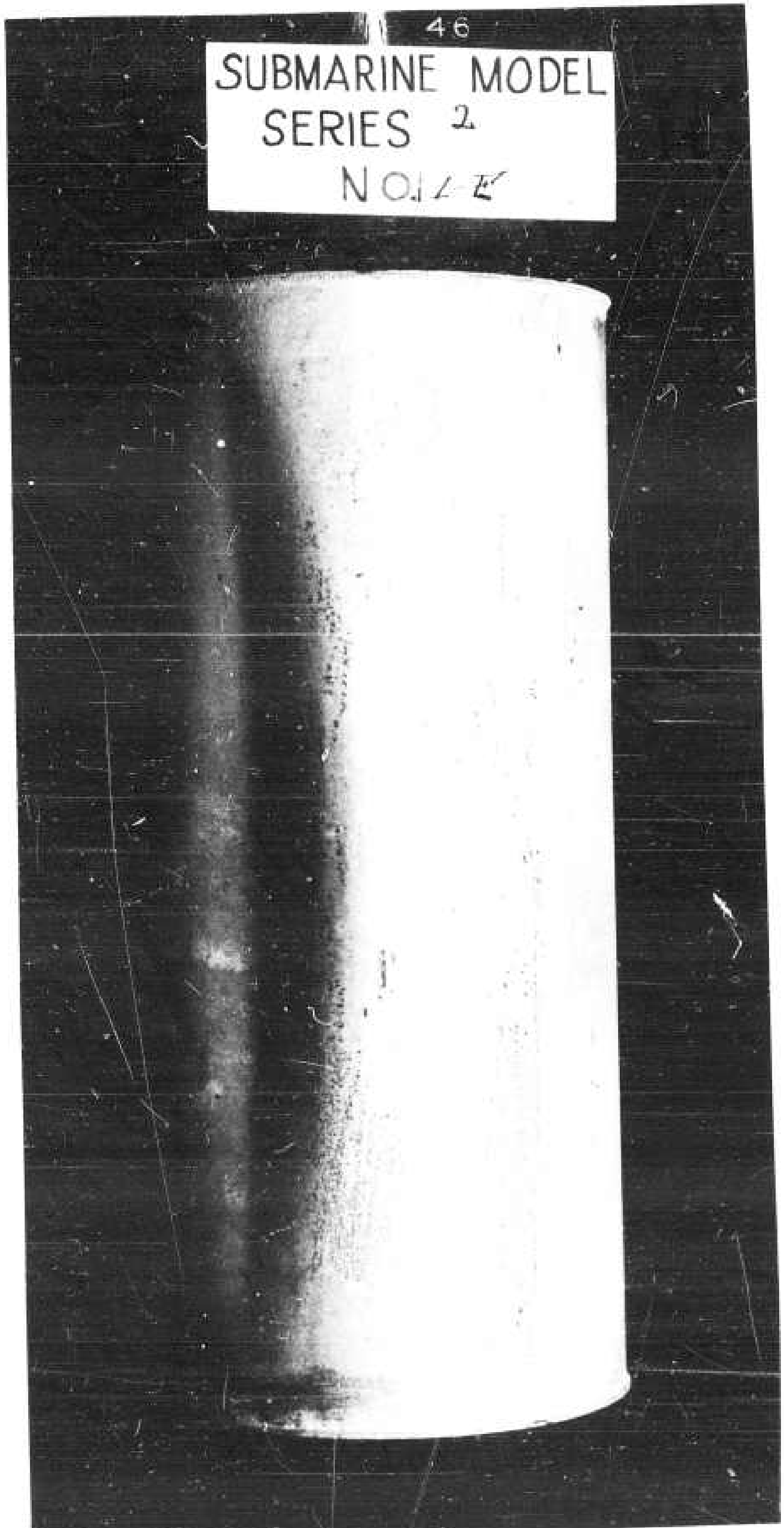
MODEL WITH OUTSIDE FRAMES SPOT WELDED TO SHELL. FRAMES ARE IN SHAPE OF I BEAM WITH ONE SIDE OF OUTER FLANGE REMOVED. NOTE THAT FRAMES SHOWED NO SIGN OF FAILURE.



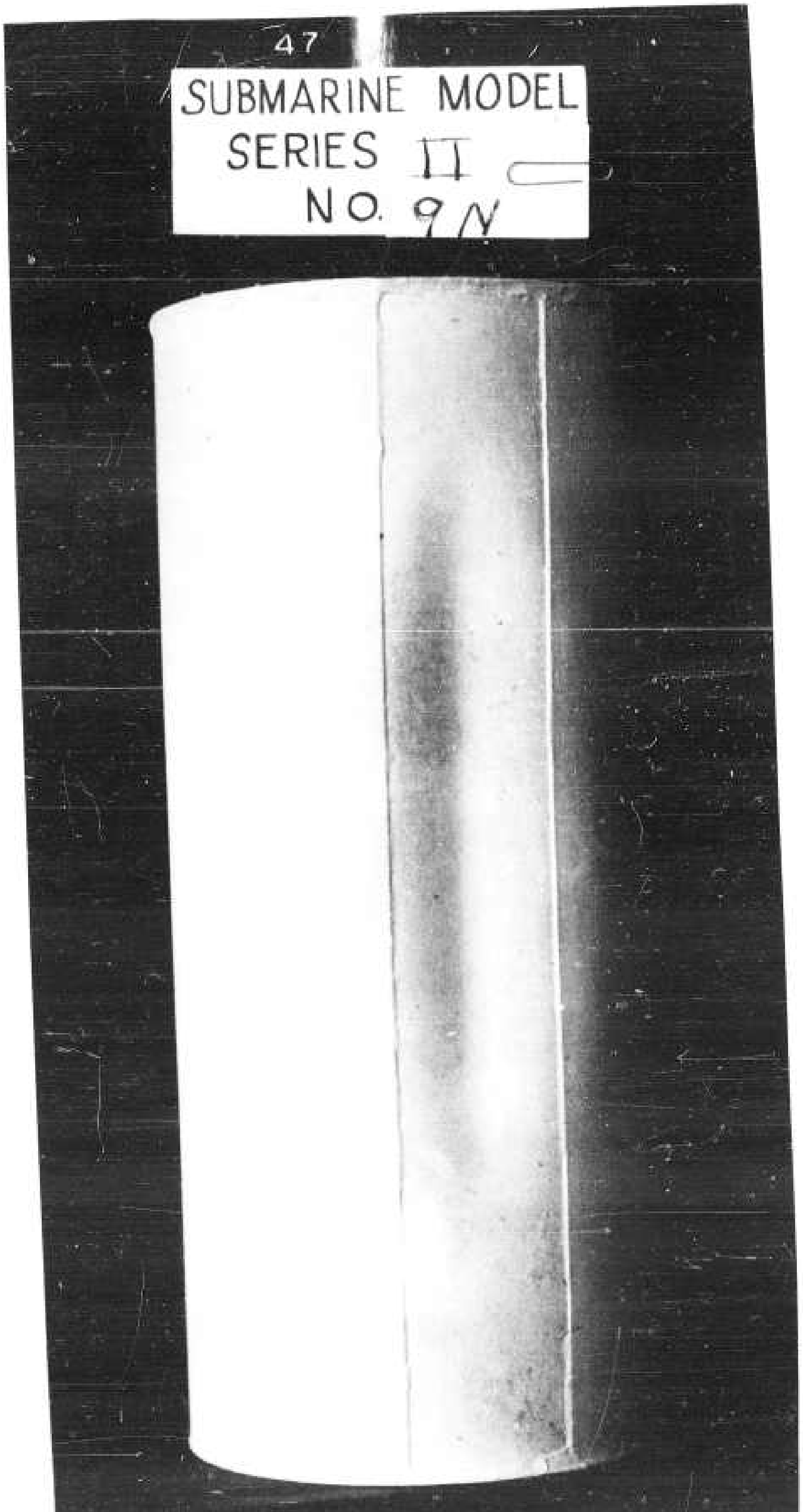
THE POSITIONS OF THE FRAMES ARE SHOWN BY VERY SLIGHT PARALLEL RIDGES AROUND THE SHELL; BETWEEN THE RIDGES ARE VERY SHALLOW DEPRESSIONS CAUSED BY A SMALL PERMANENT SET OF THE SHELL. THE CHECKERBOARD PATTERN OF BULGES IS MOST PRONOUNCED. BULGES 1, 2, 3, AND 4 ARE INWARD WHILE BULGE 5 IS OUTWARD. THE BULGE AT 7 WAS ORIGINALLY OUTWARD, BUT UNDER THE INFLUENCE OF INCREASED PRESSURE IT COLLAPSED AND WRINKLED INWARD BETWEEN BULGES 6 AND 8.



TYPICAL FAILURE. NOTE APPARENT
WEAKNESS DUE TO SEAM, WHICH CAUSES
IRREGULARITIES IN LOBE FORMATION.



MODEL 6"DIAMETER,
15" LONG, NO FRAMES,
NO STRAP ON SEAM



MODEL 6" DIAMETER
15" LONG, NO FRAMES,
STRAP ON SEAM COVERS
.895 OF CIRCUMFERENCE